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MODERN CONCEPTS OF FOOD UTILIZATION

By RUTH WOODS

Because the food we eat is the ultimate source of bodily energy it is natural to suppose that variations in the quality and quantity of this food will be reflected in the quality and quantity of the work output. Many theories concerning the influence of diet upon muscular efficiency and performance have been forthcoming. A large number of these have been based on little more than superstition and tradition. Others, based on "experiments" which, because of poorly controlled conditions and reliance upon physiological standards of questionable meaning, have merely added to the confusion particularly characteristic of this field of investigation.

In the light of modern concepts of energy metabolism — particularly those concerned with carbohydrate metabolism and its relation to muscle activity — it may be possible to evaluate the great mass of confusing data which has accumulated. Only then will it be learned whether the proper choice and timing of food intake can increase the productivity of the industrial worker, promote superior physical performance in the athlete; heighten physical stamina and endurance in the soldier; enhance the all-around efficiency and usefulness of the average man and perhaps, better his game of golf or tennis. The present Review will discuss these modern concepts of food utilization as a background for the interpretation of the interrelationships between nutrition and physical performance.

Food as Fuel:

The human or animal body has been likened to a machine. Like any other machine it must be provided with fuel in order to permit it to function. The body requires a continuous supply of fuel because the living machine is never inactive. Even when the body appears to be most quiescent, as in sleep, the invisible internal machinery is pumping blood through the body; stimulating respiratory exchanges through the lungs; digesting food; manufacturing enzymes and hormones; collecting waste products; breaking down and resynthesizing the innumerable products of metabolism.

The work efficiency of the body—the percentage of total energy converted to work—is generally considered to be about 30%, which compares favorably with the efficiency of a typical machine such as the gasoline engine. The remaining 70% of the energy supplied by the fuel is converted to heat. In the case of a machine this production of heat is usually considered as waste or as a by-product. In the body, however, the "by-product" heat is of considerable importance in maintaining body temperature. As a matter

of fact, under extreme conditions of cold as in the Arctic, extra caloric intake is required for heat maintenance alone.

The fuel for the living machine is food. The conversion of food to heat and mechanical energy is brought about by the oxidation of the food constituents—ultimately to carbon dioxide and water. Unlike the fuel of other machines, food not only maintains body temperature and provides energy for muscular activity, but ultimately becomes part of the fabric of the human machine as well.

Types of Food: The food constituents are divided into three basic groups: Protein, fat and carbohydrate. It was formerly thought that these three types of foodstuffs followed separate metabolic pathways and performed separate physiological functions. Recent studies in intermediary metabolism, particularly those using isotopic tracers (1, 2) have completely revised this concept. It is now known that the intermediary metabolism of all three of these foodstuffs, once having passed a certain stage, gives rise to a number of identical intermediary products (3). These products have been envisaged as constituting a dynamic "pool" into which, on the one hand, degradation products of both food and tissue breakdown are merged and from which, on the other hand, the body can withdraw any one or any combination of these degradation products with which to synthesize new metabolic materials or tissue constituents.

The concept of a dynamic equilibrium between food and tissue components and among the major foodstuffs themselves answers the much discussed question as to the interconvertibility of one foodstuff to another. It is now apparent that while one foodstuff is not directly convertible to another (as, for example, protein into carbohydrate), it is ultimately mutually interconvertible with all of the foodstuffs because the common products of its intermediary metabolism can be used, in a variety of combinations, to synthesize more of the same or of any of the other foodstuffs.

The fact that the three foodstuffs are largely interconvertible* means that, when necessary, they can substitute for each other in the body economy, especially as sources of energy. Life cannot be maintained on any one of these three foodstuffs exclusively, however, because the organism cannot synthesize certain metabolic essentials such as the essential amino acids, the essential fatty acids, the vitamins and the minerals. These must be provided, preformed, in the diet. It so happens that only a mixed diet of natural foods

*Fats and carbohydrates do not contain nitrogen. Accordingly, some protein must be present in the diet. Once there is a supply of nitrogen in the body it can be utilized, together with products of fat or carbohydrate (or other protein) metabolism from the "pool," to synthesize new protein material.

containing all three major foodstuffs will provide the required amounts of all the accessory food factors.

Mechanics of Fuel Utilization:

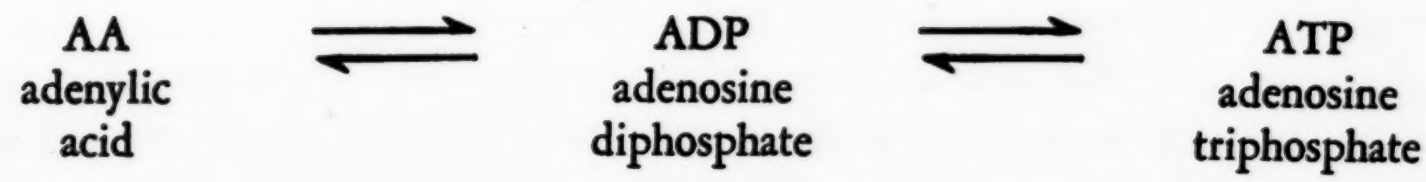
In a chemical reaction, the products and reactants have energies corresponding to and characteristic of their atomic and molecular structures. The difference between the total chemical energy of the products and the total chemical energy of the reactants is the amount of energy evolved (or absorbed) in the reaction.

In a reaction, chemical energy may be converted to heat, as in the oxidation of carbon to CO_2; or to electrical energy, as in a battery; or to mechanical energy, as in an explosion.

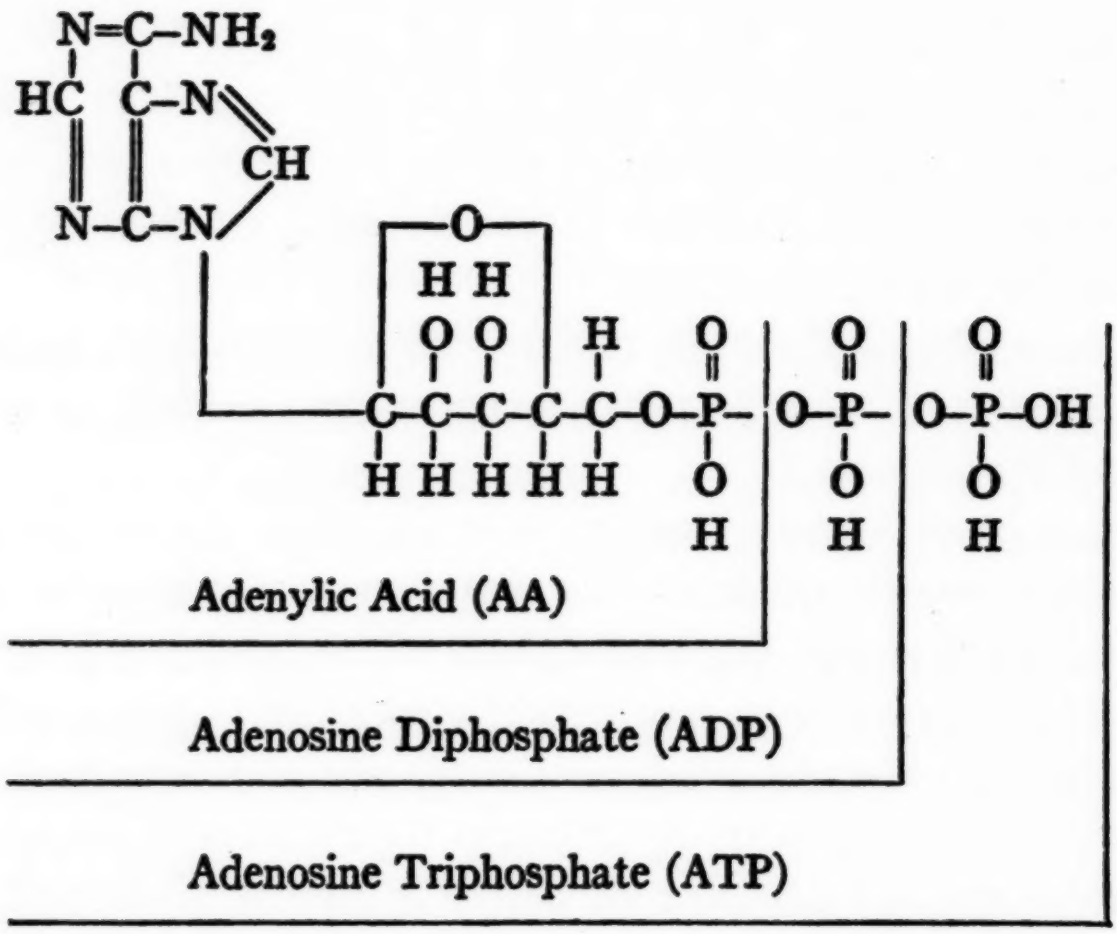
In the body, the chemical energy resulting from the oxidation of foodstuffs, or of their metabolic degradation products, may also be converted to heat; or to electrical energy (to a very small extent in nerves) or to mechanical energy. The conversion to mechanical energy takes place only in muscle tissue, whereas heat may be produced in any tissue of the body. The study of this conversion, in muscle, of chemical to mechanical energy, is one of the most important and complex problems in biochemistry and physiology. As a result of the brilliant researches of Szent-Györgyi, Engelhardt, Lohmann, Parnas, Meyerhof, Cori, and others (4-11), it is known that the energy of muscular contraction is obtained from biological oxidations by means of the mechanism of various phosphorylation processes.

The protein myosin is the contractile element which is responsible for the mechanical action of muscle. Myosin is present in the muscle in the form of threads or fibrils, bundles of which constitute muscle fibers. The myosin fibril can exist in a stretched or contracted state like a rubber band. Metabolic energy is required to stretch the fibrils, while the external force exerted by the contracting muscle is a result of the contraction of the stretched fibrils.

The energy-rich compound adenosine triphosphate, ATP, is the immediate source of the chemical energy converted by myosin to mechanical energy. The energy required to form ATP from its precursor, adenylic acid, AA, is obtained, in turn, by the oxidation of such carbohydrate derivatives as phosphopyruvic acid, glyceraldehyde and others. ATP can also give up its energy to convert a lower energy foodstuff, as glucose, to a higher-energy storage product, glycogen. Indeed the reversible system (shown below) seems



to be the central mechanism for energy transfer not only from chemical energy to mechanical energy, but also from one form of chemical energy to another. The formulas are:



In terms of the present concept any metabolic reaction (whether of carbohydrate, fat or protein) which can supply energy to convert AA to ATP can serve as a fuel for muscular exercise. This applies not only to the carbohydrate derivatives cited but also to products like α and β ketoacids derived from protein and fat.

Relative Value of Foodstuffs as Sources of Body Energy:

Bearing in mind the dynamic equilibrium of the three major foodstuffs through a pool of common metabolic intermediates, as well as the fact that the oxidation of any foodstuff releases (as well as uses) energy, it is apparent that any one of these is a potential source of energy for muscular activity.

Proteins, fats and carbohydrates may each serve as a direct source of muscle energy through certain of their oxidation reactions insofar as they may be involved in the formation of ATP. Alternatively, proteins and fats may serve as a source of muscle energy indirectly by means of a preliminary conversion to glucose or glycogen. A large part of the energy of most metabolic processes not involving glucose or its metabolic products is given off as heat rather than as mechanical energy.

Because their initial metabolic pathways differ and because each is preferentially adapted to fulfill certain special physiological functions, however,

proteins, fats and carbohydrates cannot be regarded as equivalent, calorie for calorie, in their potential energy value for muscles. Whatever validity exists in the theory that manipulation of the diet will alter muscular efficiency and performance rests, in large measure, upon this distinction.

Dietary Carbohydrate: Carbohydrates are readily converted to glucose. A major portion of the energy liberated by the oxidation of glucose (ultimately to CO_2 and water) can be used for muscular fuel via ATP instead of being converted to heat. Carbohydrate, unlike fat, cannot serve as a storage fuel because the body possesses a limited capacity to store glucose (as glycogen). The tissues of the body constantly require and use carbohydrate under all physiological conditions (12). The amount stored in the body at any one time, if not replaced as used, could sustain life for only a fraction of one day (Table 1).

Table 1. CALORIC EQUIVALENT OF CARBOHYDRATE CONTENT OF NORMAL MAN (3)*

Body weight, 70 kg.; liver weight, 1,800 gm.; muscle mass, 35 kg.; volume of blood and extracellular fluids, 21 liters.

	Per Cent	*Gm.*
Muscle glycogen	0.70	245
Liver glycogen	6.00	108
Blood and extracellular fluid sugar	0.08	17
Total body carbohydrate		370 gm.
Caloric equivalent (370 x 4.1)		1,517 calories
Caloric requirement (sedentary occupation)		2,800 cal. per 24 hr. or 116.7 cal. per hr.
Total body carbohydrate could supply caloric needs for (1,517 ÷ 116.7)		13 hr.

Thus unless adequate amounts of carbohydrate are eaten daily, the needs of the body must be met by the conversion of other foodstuffs to carbohydrate. On the other hand, when the storage limit for glycogen is reached, additional carbohydrate in excess of caloric needs is converted to fat.

Dietary Protein: Ingested protein may follow any of several metabolic pathways simultaneously. Amino acids derived from protein digestion may be carried by the blood to the various body tissues each of which utilizes these building stones to synthesize new proteins characteristic of the indi-

*Reprinted from "Carbohydrate Metabolism" by S. Soskin and R. Levine, by permission of the authors.

vidual type of tissue. In this manner protein becomes part of the body machinery (new tissues, enzymes, hormones) and provides for growth and repair. This function is exclusive for protein and is not characteristic of fat or carbohydrate. Amino acids not used in synthesizing protein (including those derived from tissue breakdown as well as from food) are deaminized and the non-nitrogenous portion oxidized. The deamination (removal of NH_2) of the amino acid, alanine, for example, results in the formation of pyruvic acid. Pyruvic acid is a major intermediate of carbohydrate metabolism as well, being derived from glucose. This is one example of the merging of protein and carbohydrate metabolisms in a common, reversible pathway. The oxidation of the non-nitrogenous portion of amino acids contributes to the fuel for muscular work directly (13). The non-nitrogenous portions, as part of the common metabolic pool, may subsequently be utilized for the synthesis of glucose (3, 14). This indirect conversion of protein to carbohydrate (glucose) is another means whereby part of the energy value of proteins is utilized for muscle activity. The remainder of the energy value of proteins is utilized for heat production.

Dietary Fat: Ingested fat similarly follows one or more alternative metabolic pathways simultaneously. Following digestion, absorption and transportation via the bloodstream, fat removed from the blood may be broken down and oxidized with an evolution of heat or it may be stored for future use as fuel in the adipose tissues. Oxidation of the glycerol portion of the fat molecule yields metabolic intermediates similar to those formed in carbohydrate metabolism. These may be utilized directly as a source of energy or for the synthesis of glucose and glycogen (15). Oxidation of the fatty acid moiety may also yield intermediates for glucose synthesis or may give rise to ATP for direct energy. As an example of the former possibility, acetoacetic acid (derived from fatty acid metabolism) can react with pyruvic acid derivatives (whether derived originally from protein or carbohydrate sources) thereby merging, as did the proteins and carbohydrates, in a common final pathway.

When food intake is insufficient to meet the caloric needs of the body, stored fat is mobilized to make up the caloric deficit. When food intake is in excess of caloric needs of the body *(whether taken in the form of protein, fat or carbohydrate)* the excess calories are deposited as fat in the adipose tissues. Fat serves, therefore, largely as an emergency fuel-storage material.

Caloric Values in Relation to Muscle Fuel Value:

The energy liberated by the foodstuffs during the combustion to carbon dioxide and water is usually expressed in terms of heat units or calories.

As measured in a calorimeter, the complete oxidation of the foodstuffs yields the following values:

Carbohydrates	4.1	Calories per gram
Fats	9.45	Calories per gram
Proteins	5.65	Calories per gram

In the body, protein is not completely oxidized, so that the fuel value of a gram of protein has been calculated to be about 1.30 calories less, or 4.35 calories per gram. Furthermore, the foodstuffs are not completely absorbed in the body, so that additional allowances for digestive losses must be made as follows:

	Calories 1 gm.		*Percent absorbed*		*Physiological fuel value*
Carbohydrates	4.1	×	98%	=	4 calories per gram
Fats	9.45	×	95%	=	9 calories per gram
Proteins	4.35	×	92%	=	4 calories per gram

According to these accepted values, fats yield, gram for gram, more than twice as much energy upon oxidation as do carbohydrate and protein. In spite of this fact, experimental evidence indicates that the efficiency of the foodstuffs as sources of mechanical energy does not parallel these values. The body as a whole and the skeletal muscles in particular depend more on carbohydrate for the major portion of their energy under most conditions (16). This apparent discrepancy can readily be reconciled in the light of the current concepts of intermediary metabolism outlined in the preceding section. Briefly and reduced to its simplest interpretation, it must imply that the caloric yield of carbohydrates is more completely converted to mechanical energy than those of proteins and of fats.

Summarizing the existing knowledge concerning the utilization of the various foodstuffs for muscular fuel, Gemmill (17) concludes:

> From the survey of the literature it is obvious that the use of carbohydrate is of primary importance as a fuel for muscular exercise in man. The evidence comes from the slight increase in efficiency on a carbohydrate diet, the prolongation of muscular effort when carbohydrate is ingested, the fall in blood sugar during long continued muscular exercise and the production of lactate at the beginning of exercise and during severe exercise. The evidence that protein is used during exercise indicates that it is of secondary importance, probably to supply carbohydrate or carbohydrate intermediates. The results of experiments on fat utilization during muscular work have demonstrated that this substance is used indirectly. There is no experimental evidence at the present time for the direct utilization

of fat by mammalian muscle. However, the indirect utilization of protein or fat must be an efficient process, since the exclusive feeding of these substances to man does not have a marked effect on muscular efficiency during short periods of exercise.

This confirms the concept that if sufficient carbohydrate is not present in the diet, it must be made by the body from other dietary materials. The eating of adequate amounts of carbohydrate, therefore, "spares" the body the work of making its fuel. This function of carbohydrate is naturally more important during moderate or severe muscular exertion than when the body is at rest and has sufficient time for the synthesis of glucose and glycogen. The great demand for fuel accompanying muscular exercise may soon exhaust the limited carbohydrate stores (17, 18, 19).

Glucose vs. Glycogen:

Most of the body carbohydrate is present in the form of glycogen, sometimes called animal starch. Glycogen is formed by the polymerization of glucose by means of the coenzyme, ATP. Glycogen is richer in energy than glucose. This extra energy accumulated during polymerization is derived via ATP from the *oxidation* of other or additional glucose.

Glycogen is located directly in the muscle tissue. In emergencies when the muscle tissue requires energy faster than the blood can supply glucose for this purpose, the glycogen within the muscle cells may be utilized. This represents a definite energy advantage (12) since the stored glycogen is richer in energy than glucose itself. This does not mean that something (energy) is gotten for nothing; energy was required to form the glycogen in the first place. However, this energy was expended during a period of rest when time and energy for this conversion were available.

Soskin (13) has compared the advantage of glycogen over blood sugar as an emergency fuel to the mechanical water supply system portrayed in the diagram (Fig. 2) on the following page.

Here the water in the well represents the blood sugar, the pump represents the phosphorylating mechanisms and the tank on the roof is the glycogen store. When the tank contains stored water, the tap can deliver a rate of flow far beyond the rate capacity of the pump. The water stored during periods when the tap is closed *(rest)* is at a higher level than the original source of the water and also stores some of the energy applied by the pump. This potential energy is released when the tap is opened *(exercise)*. Too great an outflow from the tap may, of course, exhaust the stored water and reduce the flow from the tap to the rate at which the pump is capable of operating.

The ingestion of carbohydrate is followed by the absorption of its diges-

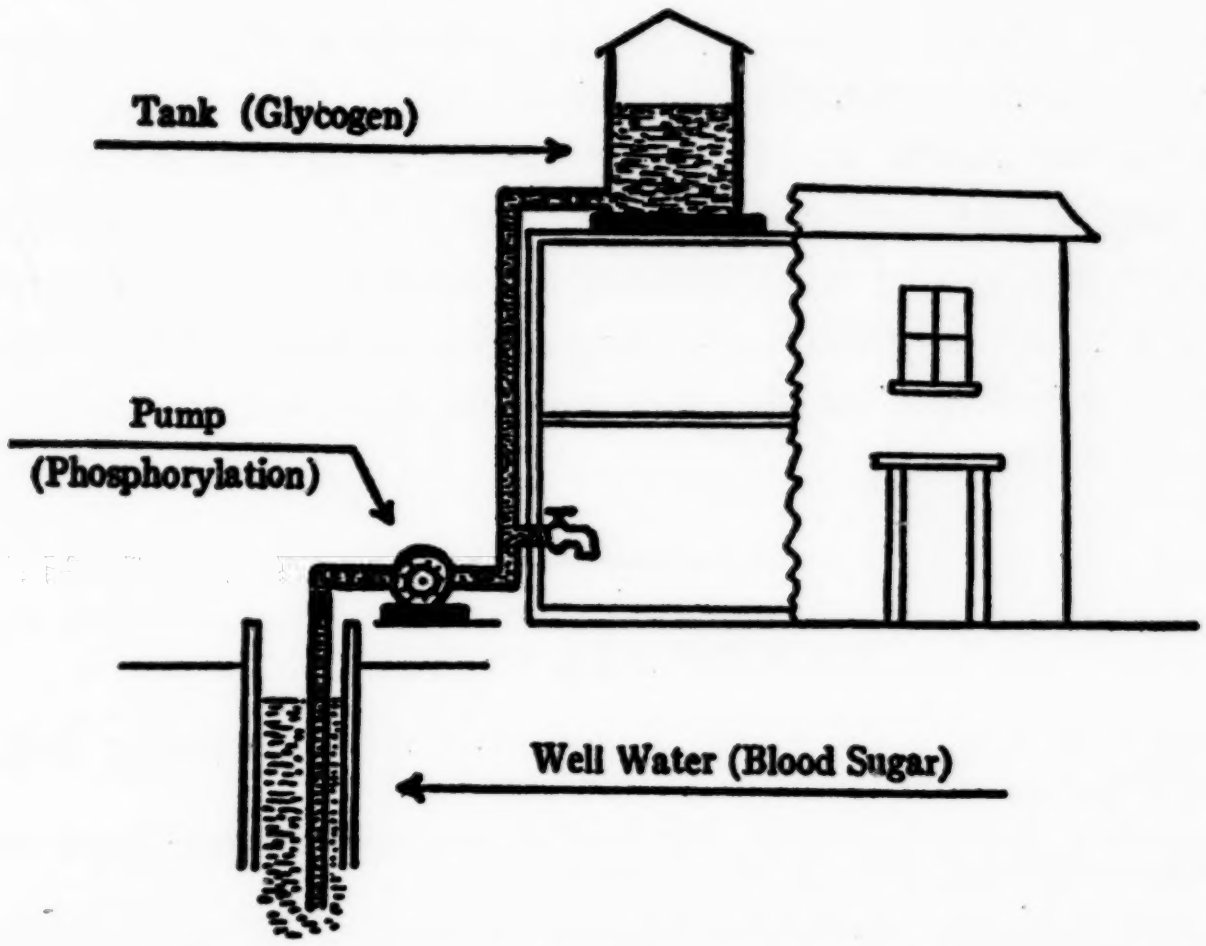


Fig. 2. Mechanical analogy, illustrating the advantage of tissue glycogen over blood sugar as an emergency fuel (3).*

tion product, glucose, into the blood. If there were no provision for rapid storage of glucose in the tissues, its concentration in the blood would rise steeply following a meal and much of it would be excreted by the kidney and hence lost to the body. However, much of the glucose is removed from the blood by the liver and skeletal muscles where it is stored as glycogen. This process is regulated by the hormone, insulin. Since carbohydrate is constantly being utilized in the body, the reserve stores of glycogen are soon called upon to replenish the diminishing supply of blood sugar. This reconversion of glycogen to glucose is regulated by the hormone, adrenalin. The net result is that glucose is stored as glycogen following meals and then reconverted to glucose at a rate sufficient to balance the withdrawal of glucose from the blood by active tissues.

Conclusion:

Recent investigations in the intermediary metabolism of proteins, fats and carbohydrates have demonstrated the existence of a common, final metabolic pathway for all three of these foodstuffs. Because the reactions in this common cycle are largely reversible, it is apparent that these foodstuffs are theoretically interconvertible, to some extent, in the body.

The use of these foodstuffs as fuel for mechanical energy is believed to involve phosphorylation as an essential preparatory stage. Especially im-

*Ibid.

portant in this respect is the coenzyme, adenosine triphosphate (ATP). ATP is the immediate activator of muscle fiber. The energy of ATP is obtained from the oxidation of certain specific metabolic intermediates derived from any of the foodstuffs.

The knowledge gained from these newer studies in intermediary metabolism can serve as the long sought for key to the understanding of how variations in the composition of the diet may be expected to affect muscular efficiency and performance.

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NEWS DIGEST

COMPOSITION OF COMMERCIAL VANILLA ICE CREAM

Mix *Ingredients*	*Amount lb.*	Ice Cream *Food Solids*	*Proportion %*
Cream (50% fat)	244	Milk fat	12.3
Cond. skim milk (36% solids)	133	Nonfat milk solids	10.0
Skim milk	463		
Sugars	155	Sugars	15.5
Stabilizer	3	Stabilizer	.3
Egg yolk solids	2	Egg yolk solids	.2
Total*	1000	Total food solids	38.3

*1,000 lb. of mix will make about 200 gal. of ice cream.

NUTRITIVE VALUE OF ICE CREAM: Analyses of commercial ice cream were recently undertaken in order to obtain reliable information for use in dietary calculations involving this product. The excellent nutritive value of ice cream has long been recognized from information obtained through feeding experiments and from information on the food value of its ingredients. More analyses of ice cream for its major food nutrients were deemed necessary, however, for a true evaluation of its nutritional value. Composition of a typical commercial ice cream mix used in the study is shown above.

The results of these analyses agree fairly well with those reported by the National Dairy Council for other ice creams during other years. The findings are summarized in the table below.

It is interesting to note that the iron content of ice cream is about double that of milk. The riboflavin value found by the authors of the present study is almost twice that reported by the National Dairy Council, but the average of the three reported values approximates expectations based upon analyses of the milk content. The authors point out that there is considerable variation in the vitamin A data. The ice

NUTRITIVE VALUE OF COMMERCIAL VANILLA ICE CREAM

INVESTIGATORS	ENERGY	PROTEIN	FAT	CARBOHYDRATE*	TOTAL MINERAL	CALCIUM	PHOSPHORUS	IRON	THIAMINE	RIBOFLAVIN	NIACIN	VITAMIN A	ASCORBIC ACID
	calories/ 100 gm.	*gm./ 100 gm.*	*gm./ 100 gm.*	*gm./ 100 gm.*	*gm./ 100 gm.*	*gm./ 100 gm.*	*gm./ 100 gm.*	*mg./ 100 gm.*	*mg./ 100 gm.*	*mg./ 100 gm.*	*mg./ 100 gm.*	*I.U./ 100 gm.*	*mg./ 100 gm.*
The authors	206†	3.87	12.3	21.32	0.80	0.117	0.101	0.120	0.041	0.343	0.089	720	0
National Dairy Council, May, 1944	208	3.69	11.86	21.65	0.81	0.125	0.107		0.041	0.171	0.088	472	
National Dairy Council, June, 1945	208	3.99	12.02	20.95	0.81	0.125	0.107		0.032	0.194	0.117	452	0
Average	206	3.85	12.06	21.31	0.81	0.122	0.105	0.120	0.038	0.236	0.098	548	0

*Carbohydrate obtained by difference.

†Calories determined in a calorimeter were actually 220, but this value was reduced by 14 to convert it to the usual physiological energy value.

cream made in New York from June and July cream had 720 I.U. per 100 gm., while that made in Chicago from fresh cream in June had 452 I.U. The values correspond to 21,744 I.U. and 13,662 I.U. per pound of butter with 80 per cent fat. These variations are within the range for summer butter recently reported for various areas in a nation-wide survey. The average value of 548 I.U. per 100 gm. of ice cream is higher than the figure usually given for ice cream, but this value should be approximately correct on the basis of the butter survey. The authors point out that most ice cream is made from milk fat produced in the summer months when the vitamin A content is high. — *J. Am. Diet. Assoc. 24,* 20 (1948).

THYROID ACTIVITY AND CAROTENE—A number of studies have suggested that a functioning thyroid gland is necessary for an animal to convert carotene into vitamin A. There is also a general impression that the administration of thyroxine increases the need for the vitamin. In the experiments reported here rats were depleted of vitamin A and at the same time brought into either hypo- or hyperthyroid states. Standard amounts of carotene or vitamin A were then fed, and the storage of vitamin A in the liver and kidneys was determined chemically. When vitamin A was fed, approximately the same amount was stored in hypo- and hyperthyroid rats as in normal rats. However, when carotene was fed, hyperthyroid animals accumulated greater stores of vitamin A than did normal rats. On the other hand, hypothyroid rats stored very little vitamin A. It would seem that the chief effect of an altered thyroid metabolism is upon the amount of vitamin A formed from carotene, rather than upon the efficiency with which vitamin A is retained in the body. Further experiments in which thyroxine was administered to hypothyroid rats showed that when the hypothyroid condition was overcome, animals fed carotene stored approximately as much vitamin A as the control groups. Thus these experiments suggest that the effect of thyroxine on preformed vitamin A is relatively minor; apparently the need for the vitamin is not increased by the use of thyroxine. Another study, made on rats whose basal metabolic rates were increased by administration of 2, 4-dinitro phenol, indicated that altered carotene metabolism associated with thyroid dysfunction is not due to changes in the basal metabolic rate *per se,* but is brought about by some other physiological action of the thyroid gland. —*J. Biol. Chem. 171,* 513 (1947).

VITAMINS IN CANNED FISH — Six species of canned fish — Atlantic mackerel, Atlantic sardines, tuna, salmon, Pacific mackerel and Pacific sardines — were tested in this study. Determinations were made of the vitamin A, vitamin D, thiamine, riboflavin, pantothenic acid, biotin, nicotinic acid, pyridoxine, and folic acid content of the various fish. No appreciable amount of vitamin A was found in the flesh of any of the fish except salmon. Small amounts of vitamin A were contained in the oils from Atlantic mackerel and sardines. The thiamine and folic acid contents of the fish were generally low. Riboflavin, pantothenic acid, and biotin were present in fair amounts. The samples proved to be good sources of nicotinic acid and pyridoxine. All species examined were good sources of vitamin D.—*J. Nutr. 34,* 633 (1947).

FLAVORED HONEYS—Honey may now be produced in six flavors—chocolate, maple, strawberry, lemon, pineapple and mint. To secure the flavored honeys, bees kept in electrically heated glass hives are fed a special mix along with pollen and a sugar-water syrup. Each flavor is appropriately colored except for the chocolate and maple flavors which require no added coloring. — *Food Fld. Rpt. Dec. 22,* (1947).